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FY93 End of Fiscal Year Letter
and Final Technical Report
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ONR CONTRACT INFORMATION

Contract Title: Continuing Research on Friction and Wear of Materials

Performing Organization: The Ohio State University

Principal Investigator: D. A. Rigney

Contract Number: N00014-92-J-1608

R & T Project Number: pri 6014-05

ONR Scientific Officer: P. P. Schmidt, ONR Code 3312

Enclosure (1)

FISCAL YEAR AND FINAL REPORT

on

CONTINUING RESEARCH ON FRICTION AND WEAR OF MATERIALS

to

The Office of Naval Research

March 21, 1994

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The Ohio State University
116 West 19th Avenue
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A. DESCRIPTION OF THE RESEARCH GOALS AND APPROACH

This project was designed to provide new information on the effects of ion implantation on surface (adhesion, chemical effects) and subsurface (deformation) effects during unlubricated sliding of metals. The base materials are copper and iron. Thus, in some samples there should be mainly structural changes caused by implantation (e.g., Fe into Fe, Cu into Cu), while in others there will be composition changes as well (e.g., Cu into Fe, Fe into Cu). Copper and iron were chosen because of the considerable amount of literature available for comparison of results from testing of these metals. Also, their hardness values and deformation behavior are different, the OSU group has experience with both metals, and the phenomenon of selective transfer, extensively studied in the former USSR, usually involves both Cu and Fe.

The project was originally designed to address questions raised at a workshop at Argonne National Laboratory in 1988(1), in particular questions associated with separating surface and subsurface effects. Recognizing that these may interact in ways which make them difficult to separate, we have attempted to use ion implantation of samples tested in vacuum in a pin/disk sliding system. Because geometric effects are known to be important, we are using both Cu/Fe and Fe/Cu configurations (pin/disk). There are thus 36 different combinations of pin/disk for each implanted thickness used, because each component can be Cu, Fe, Cu(Cu), Fe(Fe), Cu(Fe) or Fe(Cu), where the species in parentheses is the implanted species.

B. PROGRESS AND SIGNIFICANT RESULTS IN THE PAST YEAR

Brief Summary

The project was completed during 1993. The student completed all requirements for the Ph.D. degree during the summer of 1993 and received her degree in December, 1993. In the previous fiscal year report, a series of problems was described, most of which were solved by the student herself. During 1992-93, the implantations of test specimens, which had been delayed as described in the previous report, were completed at Mound Laboratories. Initial sliding tests with implanted specimens showed that the pin/disk test device required rebuilding to allow operation with very low normal loads. This problem had been anticipated during the previous reporting period, so we were prepared to design and build a new system which uses a new loading arm with ball bearing pivots. With this new system, testing of the implanted specimens proceeded smoothly.

Sliding tests were performed using pin/disk apparatus in vacuum with a normal load of 3 g and sliding speeds of 13-30 cm/s. Friction was monitored using strain gauges arranged in a full bridge circuit. Specimens were characterized using SEM, EDS, TEM, AES and nanoindentation. Computer modeling of the implantation process aided interpretation of the results.

Self-implanted samples gave lower or equal values of friction coefficient compared with the unimplanted samples for most test combinations. The decreased friction may be due to the increased hardness from grain refinement and defect formation during ion implantation. Friction behavior of the materials implanted with different species compared with that of the self-implanted materials does not correlate well with estimated changes in adhesion energy from ion implantation. Ion implantation of Cu into Fe in the Cu/Fe(Cu) system leads to increased material transfer compared with the Cu/Fe and Cu/Fe(Fe) systems. The implanted Fe disks caused larger wear scars on the Fe pins than on unimplanted Fe disks. Friction transitions were observed in sliding tests of Fe/Fe(i) at long sliding distances. In contrast, long term tests with Fe/Cu(i) exhibited a steady increase of friction without any sudden transition.

A persistence effect was observed with long term tests of Fe/Fe(Cu) at 3 g load and in Cu/Fe(Cu) at 50 g load. We do not believe that this results from enhanced diffusion, but, rather, from a geometric effect, in which the shape of the ball causes new implanted material to come into contact at the sides of the track, even when the implanted material in the central portion has worn away. This is consistent with the work of P. Wilbur at Colorado State University, who uses an instrument which includes radial motion of the pin

so that the pin sweeps across a wide area of the disk, thus eliminating edge effects. He sees no unusual persistence effect (2).

Full Report

1. Background:

One of the most important issues in tribology is the need to understand the relative contributions of surface (adhesion, chemical effects) and subsurface (deformation) effects. Those who work with lubricants tend to focus on surfaces and adhesion, while those who study unlubricated sliding tend to concentrate on deformation and changes in the underlying materials. The importance and the difficulty of bringing these two approaches together was discussed at a workshop at Argonne National Laboratory in 1988 (1).

Previous work in this laboratory has identified a sequence of events which involves large plastic strains, adhesion, shear instability, transfer and mechanical mixing during unlubricated sliding (5). This sequence involves both plastic deformation and adhesion. The sliding com-ponents, the mechanically mixed material and trapped debris all undergo plastic deforma-tion. Adhesion influences initial transfer and the integrity of the mechanically mixed mate-rial. It also affects the chemical composition and the volume fraction of phases in the mixed material and in the debris. These in turn affect mechanical properties such as hardness, yield strength, ductility and fracture toughness. Environmental factors (atmosphere, lubricants) influence both the deformation and the adhesion. From these considerations, it is clear that plastic deformation and adhesion are intimately connected in sliding systems (6). Experiments with the contact of field emission tips (NASA-Lewis Laboratories)(3) confirm this, as does the computer modeling of Landman (4). At the macroscopic level (7,8), Johnson has calculated the plastic strains in sliding processes using a slip-line field and concluded that the effect of adhesion is to increase the plastic strain in the softer sliding component.

Ion implantation is commonly used to create hard surface layers which are wear-resistant. Ion implantation is a unique technique which can modify both the mechanical properties and the chemistry of near surface material. It creates a surface layer which is intimately mixed with the bulk. Also, the concentration profile of the surface layer is reproducible. This project was designed to provide new information on the effects of ion implantation on sliding behavior by using a range of complementary characterization techniques for a selected set of test specimens involving copper and iron substrates and copper and iron implanted species.

During the early stages of this project, the student encountered a series of problems which she solved successfully. Here is a list of those problems: carbon contamination in the annealing system (designed and built a new annealing system); Cd contamination in ion beam system at Mound Labs from Cd plated mounting screws (changed to stainless screws); Si contamination in vacuum system (solved by changing vacuum system); Cu balls from manufacturer came with embedded SiC particles (solved by chemical polishing); electrical noise (solved by re-wiring, grounding and shielding); system insensitivity to low loads (designed and built new test system with ball bearings); and long delays by Mound Labs in implanting our specimens (associated with plans to shut down Mound Labs--part of changes in the world situation). During the delays related to these problems, the student became proficient with several scanning and transmission electron microscopes and with specimen preparation for those instruments. She also reviewed the literature systematically and wrote a section of her thesis based on that review.

2. Experimental Procedure:

Sliding tests were performed using a pin-on-disk apparatus in a vacuum chamber. The rotating disk was horizontal and fixed to a motor shaft. The load was a dead weight on the pin. A detailed description of the apparatus is given in references 9 and 10. The test materials were chosen to be pure Fe and Cu, because their mechanical properties and surface energies are different and because their sliding behaviors have been extensively studied. The disks were 23 mm in diameter and 5 mm thick. The Fe pins were machined to have hemispherical tips of 6.35 mm diameter, and the Cu pins were balls of 6.35 mm diameter obtained commercially. The source, purity, microhardness and annealing temperatures of the specimens are listed in Table 1. The disks were polished through 120, 240, and 400 grit SiC papers,and annealed in a 5% H_2 and 95% Argon atmosphere at a temperature of 400°C for the Cu disks and 600°C for the Fe disks. After annealing, the disks were further polished to 0.05 mm using alumina and distilled water for Cu and colloidal silica for Fe. After each step in polishing, the specimens were ultrasonically cleaned in acetone and methanol successively and blown dry using Dust-off. The pins were chemically polished. The Fe pins were chemically polished in a mixture of 94 ml H_2O_2 and 6 ml HF and washed in succession in H_2O_2, distilled water and ethanol, and blown dry (11). The Cu balls were chemically polished in a mixture of 55 ml H_3PO_4, 25 ml acetic acid and 20 ml HNO_3 with two droplets of HCl, and cleaned in distilled water followed by methanol (11).

Some of the disks and pins were ion implanted at EG&G Mound Applied Technologies, Miamisburg, Ohio. The ion species were Cu and Fe produced from the chlorides. The parameters of ion implantation for Cu^+ and Fe^+ were: 2×10^{16} Cu^+/cm^2

@ 200 keV, 3 x 10^{15} Cu^+/cm^2 @ 60 keV, 3.5 x 10^{15} Cu^+/cm^2 @ 35 keV; 3.4 x 10^{16} Fe^+/cm^2 @ 200 keV, 3.0 x 10^{15} Fe^+ $/cm^2$ @ 35 keV. Multiple energies were used so that a plateau in concentration close to the surface could be obtained.

The pin-on-disk apparatus was enclosed in a bell-jar which can be evacuated using a mechanical pump and a turbomolecular pump. All tests were performed in a vacuum of ~2- 5 x 10^{-6} Torr. The load used was 2.88 g (10.7 g was used in some tests). Sliding distances were 0.034, 0.45 and ~45 m. Sliding speed was in the range of 13~30 mm/s.

The implanted layer was characterized using TEM, nanoindentation, and Auger Electron Spectrometry (AES) in the Chemical Analysis Lab at The Ohio State University. Computer modeling to obtain predicted implantation profiles was done by Oak Ridge National Laboratory. Friction force was measured using strain gauges in a full bridge circuit. Wear track morphology and the degree of material transfer were studied using SEM and EDS.

3. Results and Discussion:

There are 36 combinations of tests in this study, namely pins and disks of Fe, Fe(Cu), Fe(Fe), Cu, Cu(Fe), Cu(Cu), respectively, with the implanted ion species in parentheses. Each test combination will be denoted by A/B, where A is the pin and B is the disk.

3.1 Characterization of the implanted materials

3.1.1 Concentration profiles of the implanted layers

The concentration profiles of the implanted layers were calculated using computer modeling. The concentration profiles of Fe(Cu) and Cu(Fe) disks were also measured by a Perkin-Elmer model 550 ESCA/Auger spectrometer. The electron gun was operated at 3 keV and 20 mA/cm^2. The Ar^+ beam was at 2 keV, with a beam current density of 100 mA/cm^2. The depths of sputter craters were measured using a profilometer, which were approximate since the roughness of the sample surfaces was of the same order of magnitude as the depth of the sputter crater. Table 2 lists the results of the computer modeling and AES measurements in terms of the maximum concentration, the peak depth, and the total depth of the implanted layer by taking ~10% of the peak value on the concentration profile as the zero of implanted ion concentration. The discrepancy in the results of AES and computer modeling of Cu(Fe) was caused by the different sputter rates of Fe and Cu, as indicated by the measurements of the sputter crates of Fe and Cu films vapor deposited on two SiO_2 mirror blanks.

3.1.2 TEM studies of the implanted layer

TEM samples were prepared by a back-thinning method from plain Fe, Fe(Fe) and Fe(Cu) disks. The Fe sample gave bending contours and single crystal diffraction patterns

or elongated dots in the ring patterns. The grain size in the implanted layer ranges from 0.02 mm to 0.5 mm, whereas the original grain size before ion implantation is larger than 100 mm. Thus there is grain refinement by ion implantation. It was also observed that the defect density in the implanted samples was higher than in the unimplanted sample.

3.1.3 Nanohardness measurements

Nanohardness measurements were made using a Nanoindentor2™ at Conner Peripheral, California. Each run consisted of ten positions 5 mm apart in a rectangular area with 5 points in a row. Each indentation consisted of loading, holding and unloading. The loading rates used during indentation were 1.5 nm/s, 5 nm/s and 18 nm/s for applied loads of 5 mg, 20 mg ad 50 mg, respectively. Fig. 2 shows the plots of the nanohardness vs. the depth of plastic deformation for disks of Fe, Fe(Fe), Fe(Cu), and Cu, Cu(Cu), Cu(Cu). The values of the average hardness indicate that the order of hardness increase is: Cu, Cu(Fe), Cu(Cu), Fe, Fe(Cu), Fe(Fe), with the exception of implanted Fe disks at 50 mg load, as shown in Fig 2. Hardness increases on the implanted disks were expected because ion implantation introduces defects (12-16), giving rise to grain refinement and metastable solid solutions (Fe and Cu have negligible solid solubility in each other) (17-19). The scatter in the nanohardness measurements were caused mainly by surface roughness. The average roughness for the disks ranged from 14 nm to 106 nm. In addition, composition variation with depth from the surface and microstructural features such as grain boundaries and different grain orientations could also contribute to the scatter (20, 21).

3.2: Sliding behaviors of the implanted samples

3.2.1 Friction

For sliding tests at the 2.88 g load and a sliding distance of 0.45 m in vacuum, the friction behavior varied from test to test for the same combination, e.g., for Fe(Fe)/Fe, one test showed smooth sliding while another showed rough sliding. Table 3 is a summary of the average friction coefficients for the 36 test combinations. The average values were obtained by taking ten points from each friction trace and taking the average of all the points from all the tests for each combination.

Comparison of the friction coefficients of the self-implanted disks A(A) and unimplanted disks A when sliding against the same pin material in Table 3 shows that friction coefficients of the self-implanted disks were decreased for the combinations of Cu(Cu)/Fe(Fe), Cu(Fe)/Fe(Fe), Fe/Cu(Cu), Cu(Cu)/Cu(Cu), and Cu(Fe)/Cu(Cu) compared with the values for the unimplanted disks under the same conditions. The friction coefficients of the self-implanted disks were not changed significantly for the other combinations with the exception of Cu/Fe(Fe), for which the friction coefficients of the

self-implanted disk was increased compared with that of the unimplanted disk. The decreased friction of the self-implanted disks relative to that of unimplanted disks could be attributed to the hardness increase due to grain refinement and defect formation by ion implantation.

Friction may also depend on the hardness ratio of the pin and disk (22). When the initial hardness ratio of the disk to pin is below ~1.0, a transition in friction occurs shortly after sliding starts; when the initial ratio is greater than ~1.0, long sliding distances are needed to reach the transition in friction. For friction in the transient period, individual local events, including local hardness ratio, may be more important than the overall properties in the steady state. In Table 3, Fe/Cu and Cu/Fe obey the hardness ratio criterion. However, for tests involving implanted materials, the friction results do not agree with the hardness ratio correlation.

Ion implantation changes the surface chemistry for materials implanted with different species. The estimated surface energies at room temperature based on the measured surface energies of liquids for Fe and Cu are 2.5 and 1.8 J/m^2, respectively (23). According to Miedema (23), the adhesion energy, defined as the energy decrease per unit contact area when two clean surfaces of metals A and B are replaced by A-B, is:

$$\gamma_{adhesion} = 0.85(\gamma_A + \gamma_B) - \gamma_{AB}^{Chem} \qquad \text{——[1]}$$

where γ_A and γ_B are the surface energies of the two metals, and γ_{AB}^{Chem} is the contribution from chemical interaction of the atoms of the two metals. For the Cu and Fe system, γ_{AB}^{Chem} is 0.4 J/m^2 (22). Thus, the adhesion energy change due to ion implantation can be estimated using equation [1]. Upon comparing friction coefficients of the self-implanted disks A(A) with the disks implanted with different species A(B), Table 3 shows that test combinations with increased friction compared with the corresponding self-implanted disks include Fe/Fe(Cu), Cu(Cu)/Fe(Cu), Cu(Fe)/Fe(Cu), Cu/Cu(Fe), Cu(Cu)/Cu(Fe) and Cu(Fe)/Cu(Fe). The increase in friction coefficient is up to 0.3. Combinations with decreased friction coefficients include Fe(Fe)/Fe(Cu), Fe(Cu)/Fe(Cu), Cu/Fe(Cu) and Fe(Cu)/Cu(Fe). The decrease is up to 0.35. The friction of Fe/Cu(Fe) does not change significantly compared with that of Fe/Cu(Cu). These changes do not correlate well with expected changes in adhesion energy caused by ion implantation.

Some long term tests were performed using Fe pins. Fig. 2 shows the plots of friction coefficients vs. sliding distance for these tests. For tests with the Fe disks (Fig. 2 (a)), a transition from low friction to high friction occurred for most tests. Some of the tests on Fe/Fe(Cu) showed very long low friction periods. After the friction transition,

friction levels became similar on all Fe(i) disks. For tests with Cu disks (Fig. 2(b)), there was no such transition, and friction traces remained smooth and friction coefficients increased slowly.

3.2.2 Morphology of wear track and transfer

The morphology of wear tracks was examined using SEM, and the extent of transfer was studied by EDS. When transfer was observed, it was often associated with deep grooves in the wear scars. The amount of transfer of Fe from the disks to the Cu balls changes in the following order: Fe(Cu) > Fe or Fe(Fe).

The wear scars on the Fe pins in Fe/Fe, Fe/Fe(Fe) and Fe/Fe(Cu) at 10.7 g, sliding for 0.45 m in vacuum were compared. The wear scar of the Fe pin for the Fe/Fe combination was small and porous, and the corresponding friction trace showed smooth sliding. The wear scars of the Fe pins for the Fe/Fe(Cu) and Fe/Fe(Fe) contain deep grooves which correlate with rough sliding in the friction trace.

For the long term tests with Fe pins sliding on Fe disks, the wear scars on the disks and pins showed typical severe wear morphologies consisting of grooves, patches and debris after friction transitions. For Fe pins sliding on Cu disks, wear morphologies on the pins and the disks were similar. The number of porous features on the wear track were different on Cu, Cu(Fe), and Cu(Cu) disks.

4. Conclusions:

i. The friction coefficients of self-implanted disks are equal to or lower than those of unimplanted disks except for Cu/Fe(i) combinations. The decrease in friction is probably due to the hardness increase from grain refinement and from defect formation by ion implantation.

ii. Friction behavior of the materials implanted with <u>different</u> species compared with that of <u>self-implanted</u> disks does not correlate well with estimated changes in adhesion energy from ion implantation.

iii. Ion implantation of Cu into Fe in the Cu/Fe(Cu) system leads to increased material transfer compared with the Cu/Fe and Cu/Fe(Fe) systems. The implanted Fe disks give larger wear scars on the Fe pins than are found with unimplanted Fe disks.

iv. Friction transitions were observed in sliding tests of Fe/Fe(i) at 2.88 g for long sliding distances. In most tests, Fe(Cu) disks showed a longer pre-transition time than Fe(Fe) and Fe disks. Long term tests on Fe/Cu(i) at 2.88 g load exhibit a steady increase in friction without a transition.

v. Persistence of the effects of ion implantation on sliding behavior has been reported many times. It is usually ascribed to unusually high diffusion. A persistence effect was indeed observed with long term tests of Fe/Fe(Cu) at 2.88 g and Cu/Fe(Cu) at 50 g. We

believe that this results from the geometry of the pin, which is in contact with implanted material even when the central portion of the track has worn away.

ACKNOWLEDGMENTS

The authors are grateful to the Office of Naval Research for support of this work. The contributions of B. D. Barton (ion implantation) and X. X. Tang (nanohardness measurements) are greatly appreciated.

Table 1: The source, microhardness and annealing temperature of the materials used in this study.

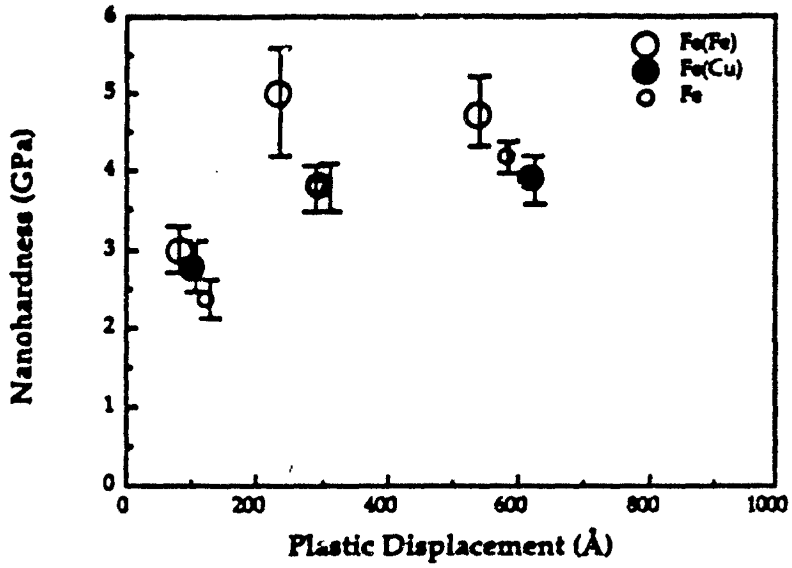
Material	Source	Purity	Specimen	Microhardness (10 g, 10 sec.)	Annealing Temperature
Fe	MRC	Very Pure	pin	87.6 ± 12.3	600 °C
Fe	Armco, Vacuum cast	99.97%	disk	77.1 ± 8.0	600 °C
Cu	Commercial	99.9%	ball	59.9 ± 8.1	400 °C
Cu	Commercial OFHC	99.99%	disk pin	40.7 ± 5.0	400 °C

Table 2: A summary of the results from computer modeling and AES measurements of implanted disks.

	Modeling			AES		
	max.conc. at.%	peak depth Å	total depth Å	max.conc. at.%	peak depth Å	total depth Å
Fe(Cu)	~4.93	340	1000	~4.0	80	900
Cu(Fe)	~5.02	440	1200	~13.0	160	650
Fe(Fe)	~5.35	540	1200			
Cu(Cu)	~6.50	120	850			

Table 3: Average values of friction coefficients for tests (including duplicate tests, in bold form) at 2.88 g sliding for 0.45 m in vacuum, with sliding speed 15–22 mm/sec, with values of the standard deviation.

		Disk					
		Fe	Fe(Fe)	Fe(Cu)	Cu	Cu(Cu)	Cu(Fe)
pin	Fe	0.47 ± 0.06	0.38 ± 0.12	0.44 ± 0.11	0.59 ± 0.18	0.43 ± 0.12	0.52 ± 0.16
	Fe(Fe)	0.47 ± 0.04	0.41 ± 0.16	0.27 ± 0.03	0.35 ± 0.01	0.38 ± 0.01	0.29 ± 0.03
	Fe(Cu)	0.60 ± 0.09	0.58 ± 0.05	0.29 ± 0.04	0.40 ± 0.05	0.46 ± 0.06	0.28 ± 0.05
	Cu	0.22 ± 0.01	0.90 ± 0.08	0.71 ± 0.06	0.65 ± 0.05	0.40 ± 0.01	0.62 ± 0.07
	Cu(Cu)	0.54 ± 0.09	0.44 ± 0.09	0.51 ± 0.06	0.78 ± 0.09	0.40 ± 0.03	0.44 ± 0.01
	Cu(Fe)	0.72 ± 0.13	0.34 ± 0.10	0.49 ± 0.13	0.57 ± 0.05	0.31 ± 0.01	0.46 ± 0.03



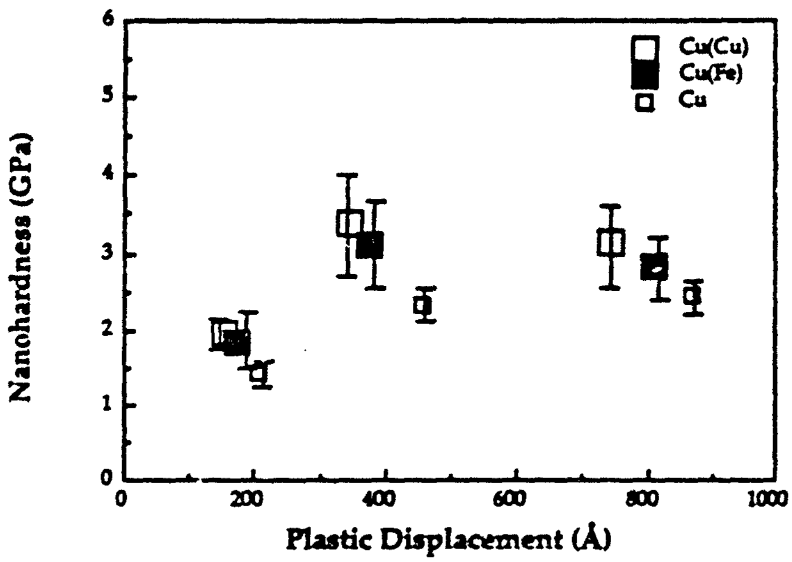
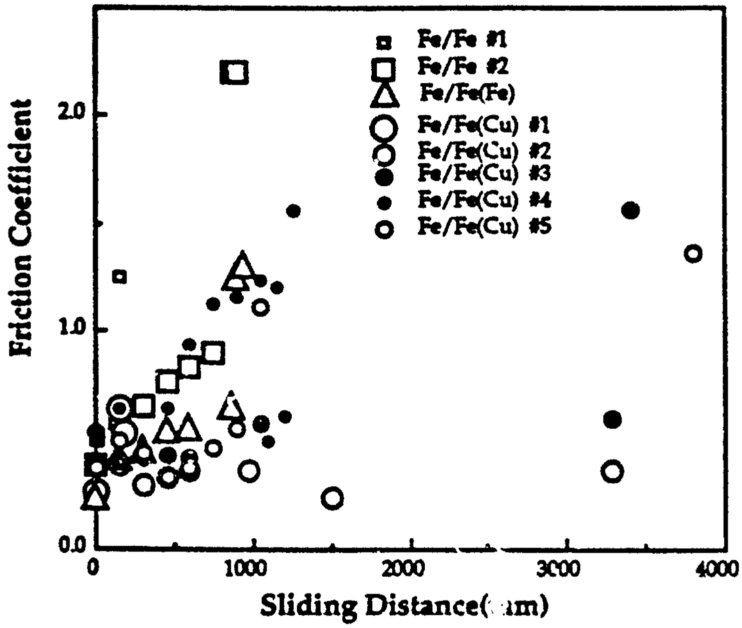


Fig. 1: Nanohardness vs. depth of plastic deformation from nanoindentation measurements. The three different plastic displacements of each disk correspond to the three loads used (5 mg, 20 mg, 50 mg). Values are the average of 6 to 8 points. The error bars represent the standard deviation.

(a)



(b)

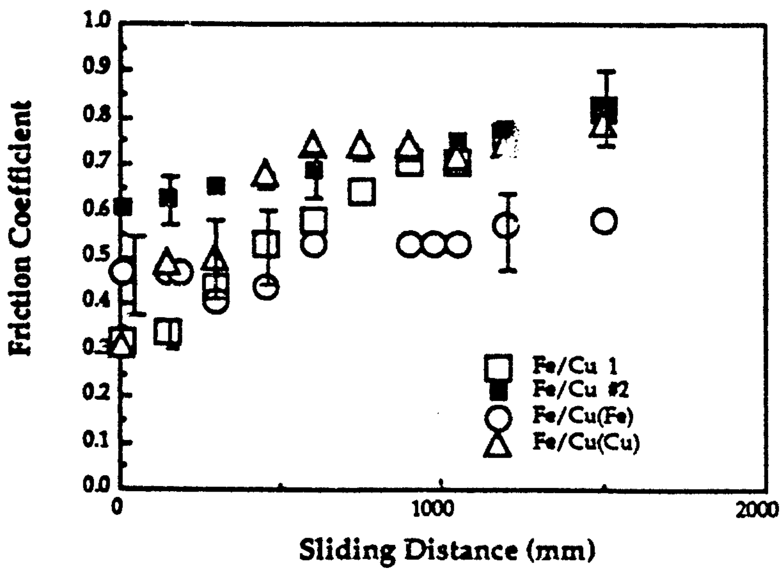


Fig. 2: Plots of friction coefficients vs. sliding distance for (a) Fe pins sliding on Fe disks, (b) Fe pins sliding on Cu disks.

C. RESEARCH PLANS FOR THE NEXT YEAR

This project has been completed, so no further experimental work is planned. However, a paper to be submitted to the journal Wear is being prepared. The authors are L. H. Zhang and D. A. Rigney.

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D. LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

S. Venkatesan and D. A. Rigney, Sliding Friction and Wear of Plain Carbon Steels in Air and Vacuum, invited for special volume of Wear 153(1992)163-178.

S. M. Kuo and D. A. Rigney, Sliding Behavior of Aluminum, Materials Sci. and Engin., A157(1992)131-143.

D. A. Rigney, The Role of Characterization in Understanding Debris Generation, in Wear Particles, Proceedings, 18th Leeds/Lyon Symposium, Lyon, France, eds. D. Dowson et al., pp. 405-412, 1992.

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D. A. Rigney, The Roles of Hardness in the Sliding Behavior of Materials, accepted for special Festschrift volume of Wear, 1994, honoring D. Dowson.

L. H. Zhang and D. A. Rigney, Sliding Behavior of Ion Implanted Metals, in preparation, to be submitted to Wear.

2. Non-Refereed Publications and Published Technical Reports

X. J. Wang and D. A. Rigney, Unlubricated Sliding Behavior of Two-Phase "White" Metals, Proc. Intertribo 93, Bratislava, Slovakia, August, 1993, vol. 1, pp. 169-173.

D. E. Larsen and D. A. Rigney, Sliding Behavior of an Al/SiC Composite against H-13 Tool Steel and PSZ, Proc. Eurotrib 93, vol. 3, pp. 83-88.

X. J. Wang and D. A. Rigney, Sliding Behavior of Pb-Sn Eutectic Alloy, Proc. ASM/TMS Sympos. on Tribology of Composites, Pittsburgh, Oct., 1993 (to be publ. 1994).

D. A. Rigney, Sub-Micron and Nano-Structures in Tribology, Proc. Workshop on Micromechanics of Small Volumes, Inst. for Mechanics and Materials, U. California at San Diego, La Jolla, CA, Feb., 1994.

3. Presentations

a. Invited

D. A. Rigney, First Plenary Lecture, The Roles of Hardness in the Sliding Behavior of Materials, Int'l. Conf. on New Materials and Technologies in Tribology, Minsk, Belarus, Oct. 6-9, 1992.

D. A. Rigney, Sub-Micron and Nano-Structures in Tribology, Proc. Workshop on Micromechanics of Small Volumes, Inst. for Mechanics and Materials, U. California at San Diego, La Jolla, CA, Feb., 1994.

b. Contributed

D. A. Rigney, The Role of Characterization in Understanding Debris Generation, in Wear Particles, 18th Leeds/Lyon Symposium, Lyon, France, Sept., 1991.

X. J. Wang and D. A. Rigney, Unlubricated Sliding Behavior of Two-Phase "White" Metals, Intertribo 93, Bratislava, Slovakia August 1993.

D. E. Larsen and D. A. Rigney, Sliding Behavior of an Al/SiC Composite against H-13 Tool Steel and PSZ, Eurotrib 93.

X. J. Wang and D. A. Rigney, Sliding Behavior of Pb-Sn Eutectic Alloy, ASM/TMS Sympos. on Tribology of Composites, Pittsburgh, Oct., 1993.

4. Books (and sections thereof)

D. A. Rigney, The Role of Characterization in Understanding Debris Generation, in Wear Particles, Proceedings, 18th Leeds/Lyon Symposium, Lyon, France, eds. D. Dowson, et al., pp. 405-412, 1992.

Enclosure (2)

E. LIST OF HONORS/AWARDS

Name of Person Receiving Award	Recipient's Institution	Name, Sponsor and Purpose of Award
D. A. Rigney	The Ohio State U.	First Plenary Lecture Int'l. Conf. on New Mat'ls. and Technologies in Tribology, Minsk, Belarus, Oct. 6-9, 1992.

Enclosure (3)

F. PARTICIPANTS AND THEIR STATUS

1. Dr. D. A. Rigney, Professor, Materials Science and Engineering, The Ohio State University, Project P.I.

2. L. H. Zhang, formerly Graduate Research Assistant, now Ph.D. (12/93). Dr. Zhang has moved with her husband, who is pursuing a Ph.D. at the University of Georgia in Athens, GA.

G. OTHER SPONSORED RESEARCH DURING FY93

1. D. A. Rigney, Selective Transfer in Tribology, NSF, Engineering Division (Surface Engineering and Tribology), SGER program, $35,000, 7/1/91-9/14/93, for one graduate student. Project completed.

2. D. E. Kim and D. A. Rigney, Surface Modification for Controlling Friction and Wear, OSU-CMR (Center for Materials Research) sponsored project, Office of Research, The Ohio State University, $44,044, Jan. 1, 1992-June 30, 1993, for one graduate student in MSE Dept. and one in Mech. E. Dept. Project completed.

3. M. Mori and D. A. Rigney, Periodic Wear in Pantograph System Used for High Speed Electric Trains, Nippon Institute of Technology, Saitama, Japan, $15,000 + salary and living expenses of visiting professor, Nov., 1992-Jan., 1994. Project completed.

H. SUMMARY OF FY92
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/PARTICIPANTS
(Number Only)

		ONR	non ONR
a.	Number of Papers Submitted to Referred Journal but not yet published:	1	0
b.	Number of Papers Published in Refereed Journals:	2	3
c.	Number of Books or Chapters Submitted but not yet Published:	0	0
d.	Number of Books or Chapters Published:	1	0
e.	Number of Printed Technical Reports & Non-Referred Papers:	1	3
f.	Number of Patents Filed:	0	0
g.	Number of Patents Granted:	0	0
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:	2	0
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:	1	3
j.	Honors/Awards/Prizes for Contract/Grant Employees: (selected list attached)	1	0
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grant:	1	2
	Grad Students: TOTAL	1	1
	Female	1	0
	Minority	1	0
	Post Doc: TOTAL	0	1
	Female	0	0
	Minority	0	1
l.	Number of Female or Minority PIs or CO-PIs		
	New Female	0	0
	Continuing Female	0	0
	New Minority	0	0
	Continuing Minority	0	0

Enclosure (4)

ONR FOREIGN TRAVEL POLICY